Search for heavy resonances decaying to bosons at CMS

Petar Maksimovic, Johns Hopkins

BOOST 2025

Today's menu

- A long time ago in a galaxy far, far away, there was a conference dedicated to doing searches with boosted objects… This talk is devoted to such searches

- Many results from CMS (too many to cover)

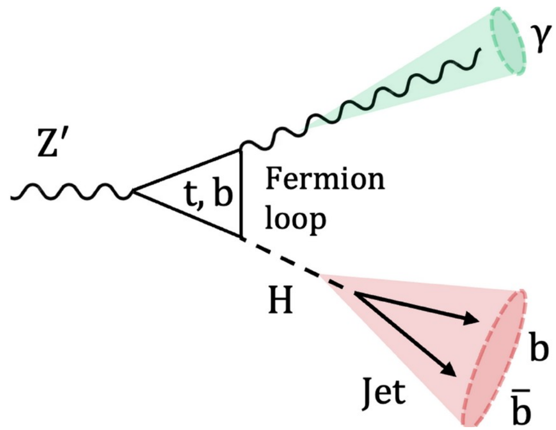
- These are recent + boosted + personal preference

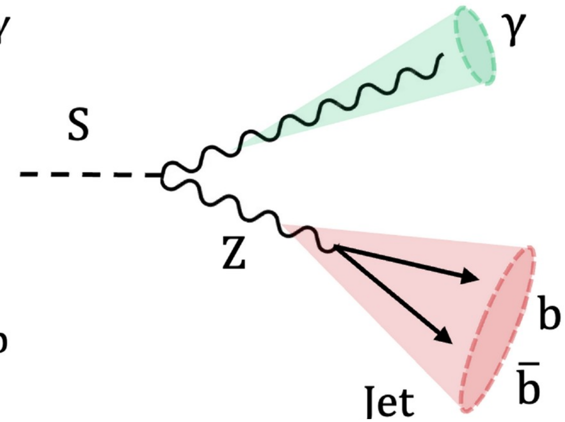
- In this talk:
  - $Z'/S \to \gamma H \to \gamma(b\bar{b})$
  - $X \to HY \to b\bar{b}WW$
  - $T' \to t\phi(H),\ \phi/H \to b\bar{b}$
  - $X \to HY \to b\bar{b} + (\text{anomalous jet})$

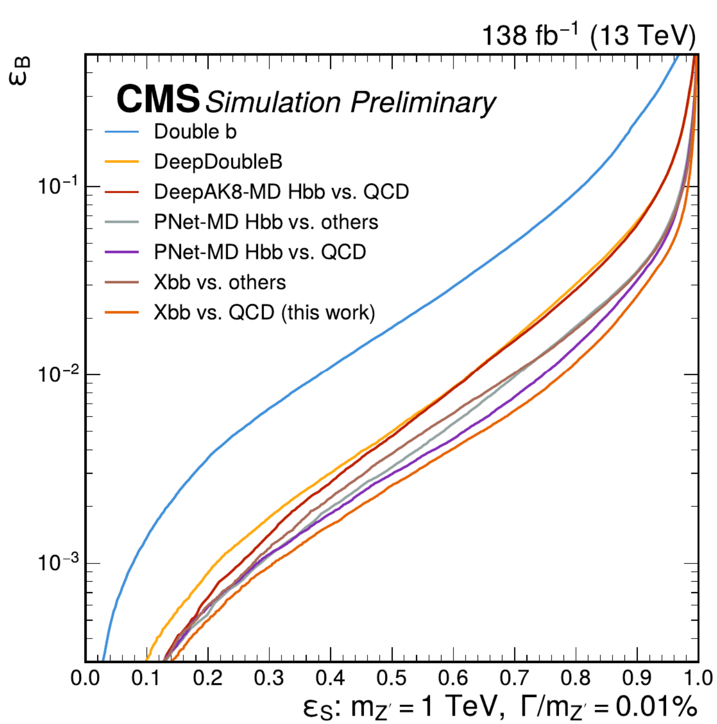
$Z', S \to \gamma H \to \gamma(b\bar{b})$

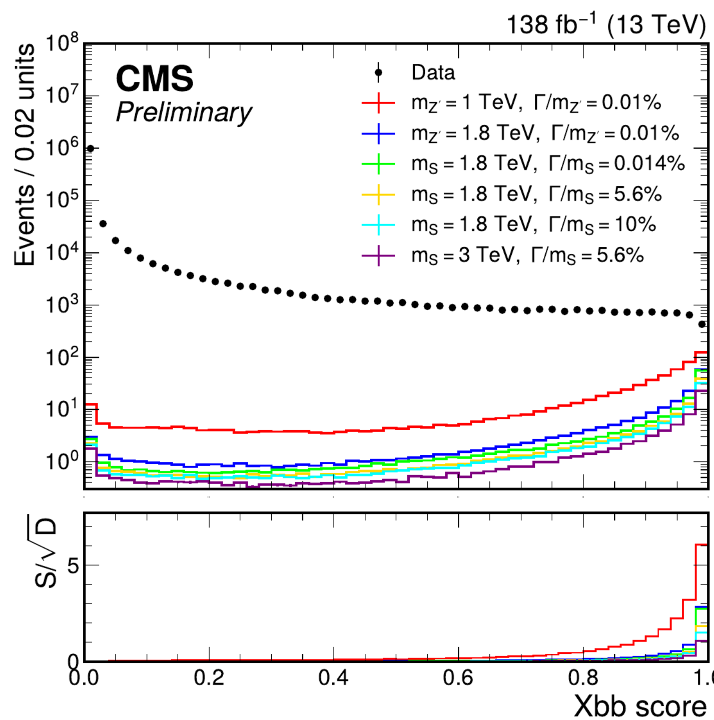
B2G-24-007

- Heavy resonance decaying to H or Z
- γ + merged $b\bar{b}$ jet, tagged with Xbb Particle Net mass.decorr. tagger









$Z', S \to \gamma H \to \gamma(b\bar{b})$

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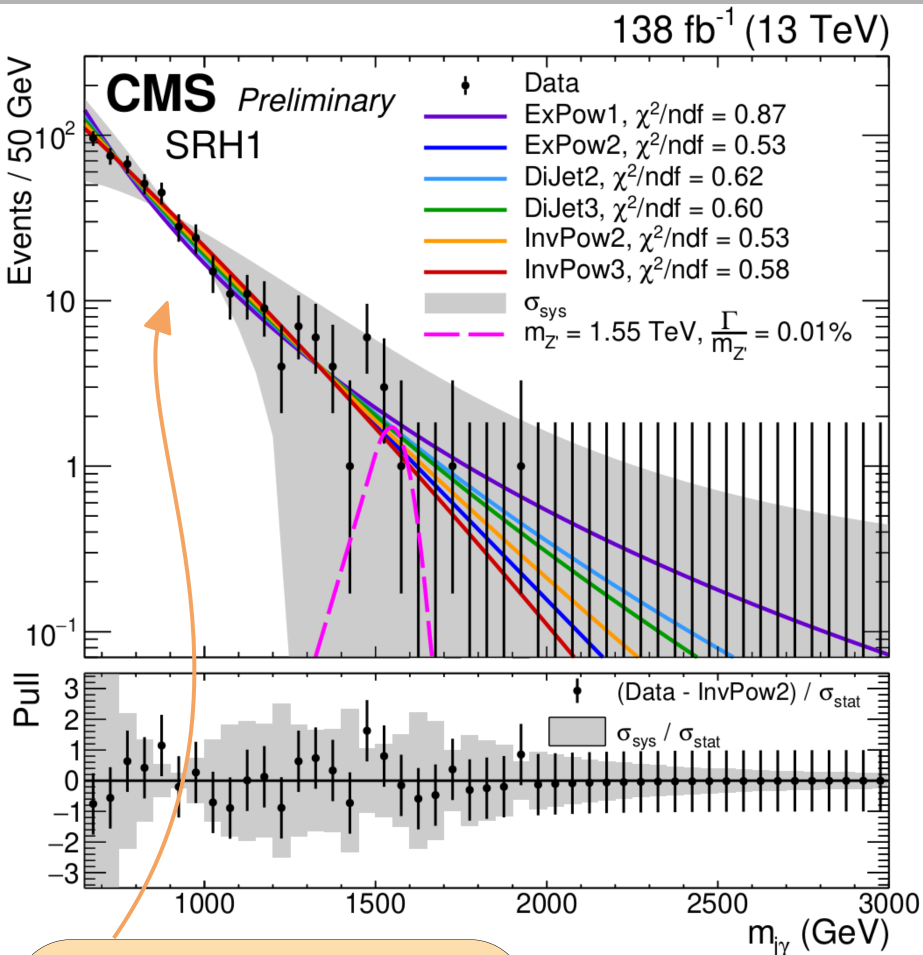
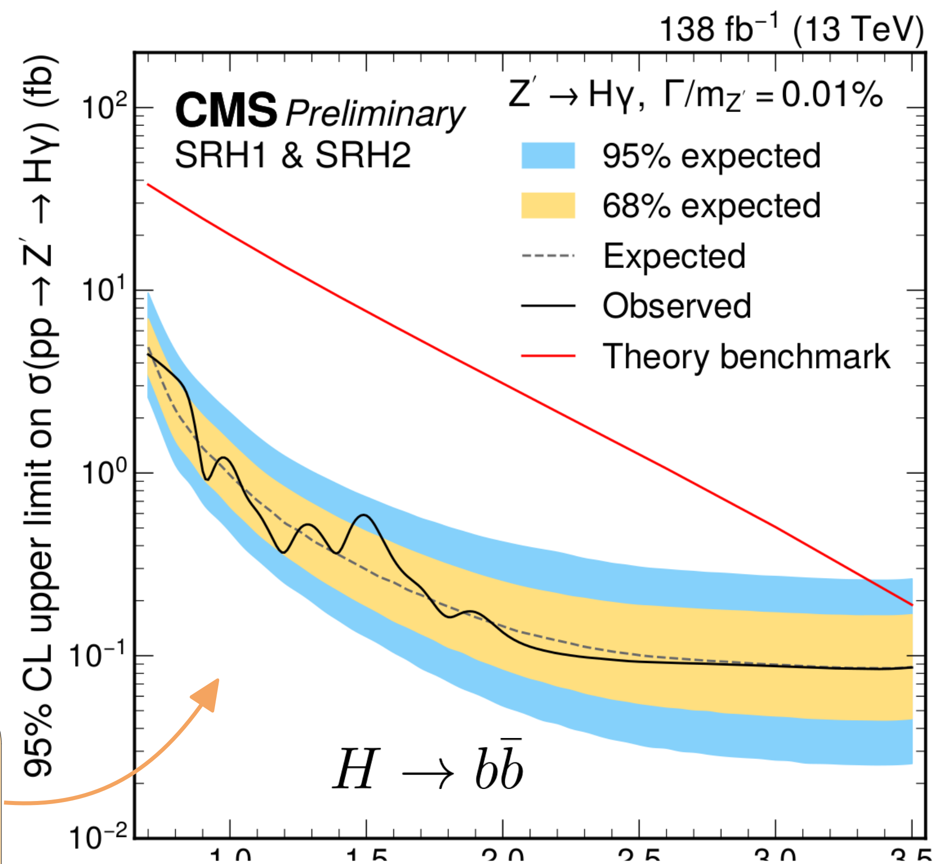


- Simultaneous fit of two SRs
- Separately for $H \to b\bar{b}$ and $Z \to b\bar{b}$



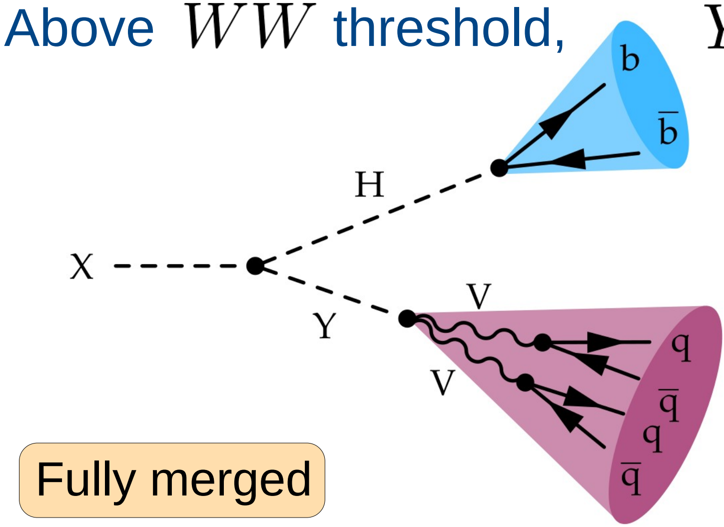
Bump hunt on top of smooth parametric distribution

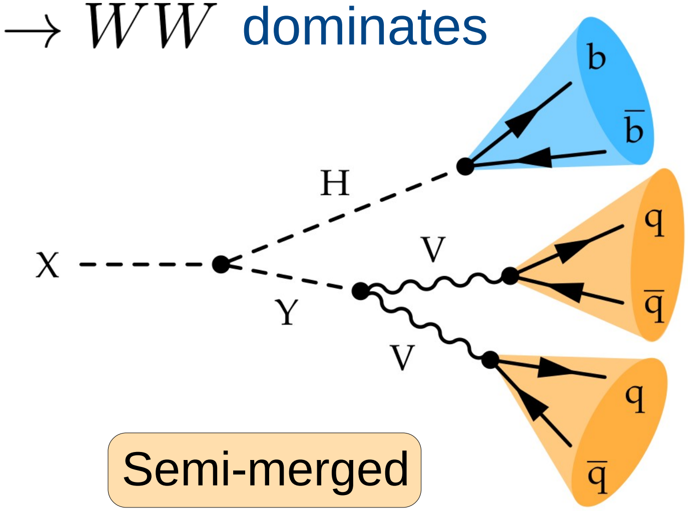
Observed limits, also for $Z \to b\bar{b}$

X → HY → (bb)WW → bb4q

B2G-23-007

- Y is a new heavy scalar, with Higgs-like BRs (e.g. TRSM)
  - Above WW threshold, $Y \to WW$ dominates





- Targets lighter Y $(m_Y \leq 0.1 m_X)$
- $Y \to WW \to 4q$ produces single jet
- Dedicated tagger built using Particle Transformer (ParT) DNN for jet tagging

- Targets heavier Y $(m_Y > 0.1 m_X)$
- $Y \to WW$ produces two $W \to qq$ jets
- Each W jet tagged with a standard $W \to qq$ tagger

X → HY → (bb)WW → bb4q

B2G-23-007

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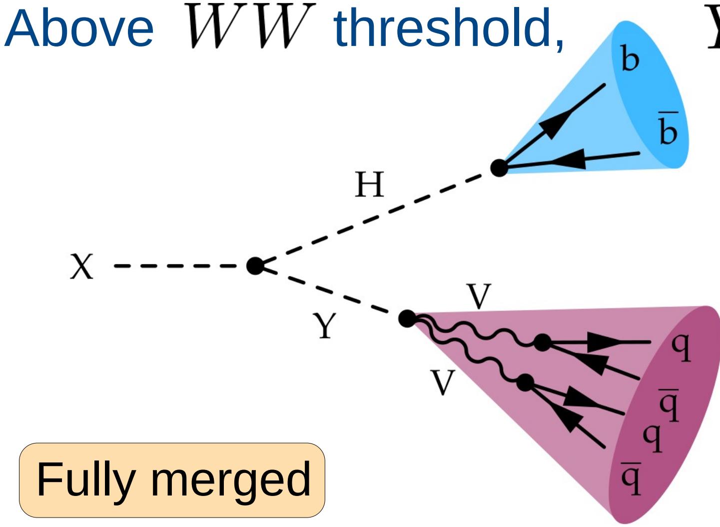

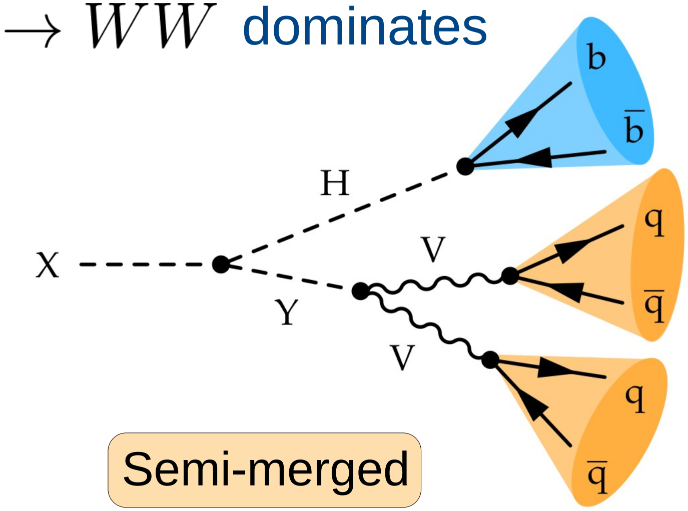

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- Targ ts
- stan agger

Lund Plane Reweighting
to estmate uncertainty
on tagger efficiency

$X \to HY \to (bb)WW \to bb4q$

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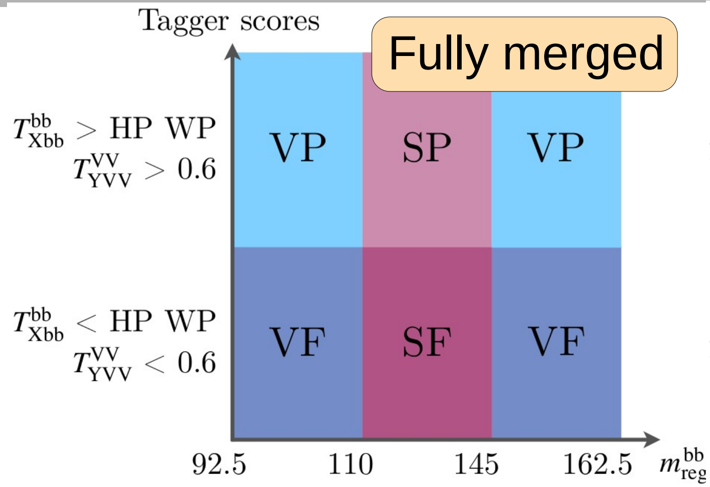
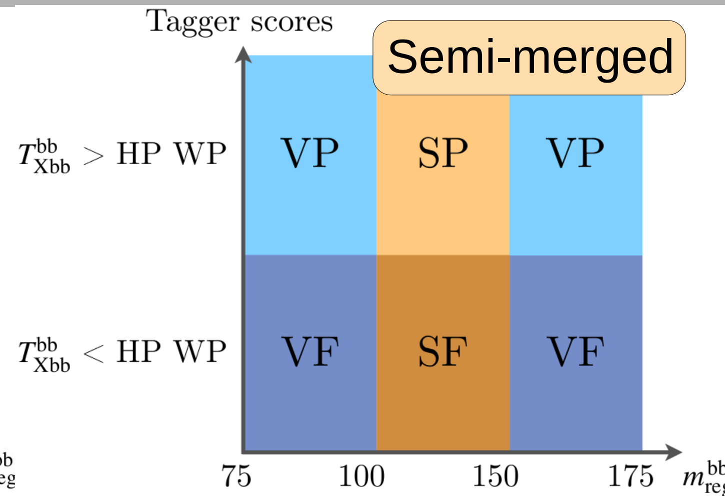
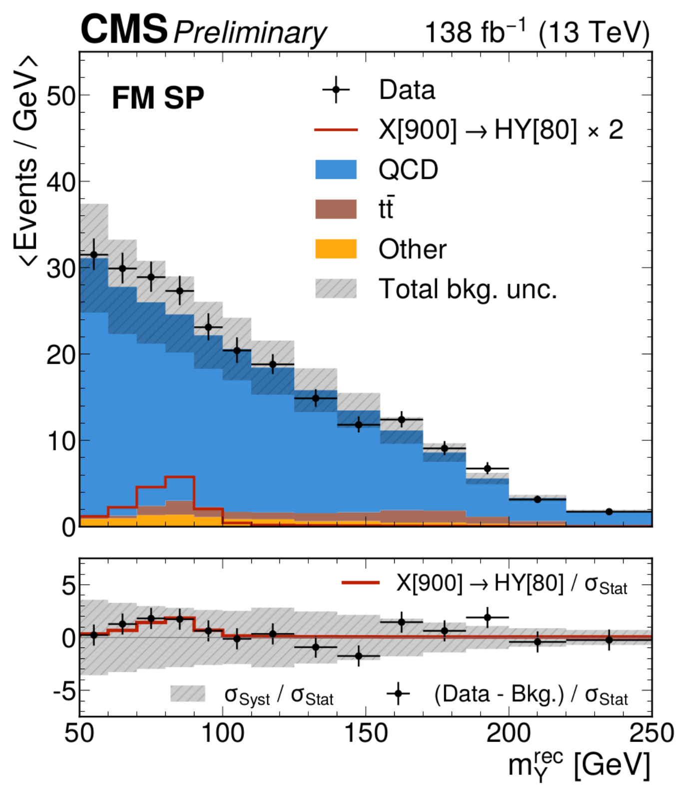
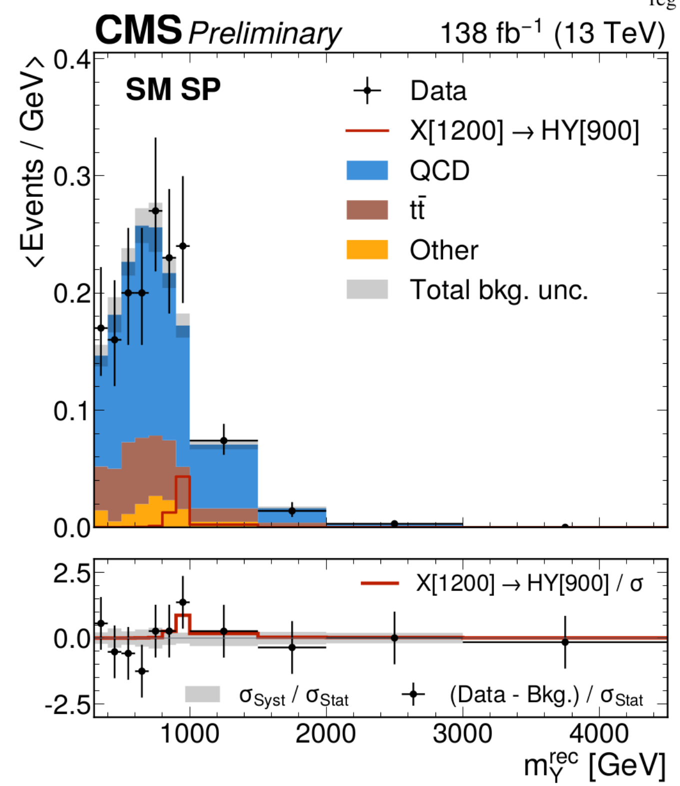
- QCD background using pass/fail ratio
- Pass[i] = Fail[i] * TF(i)









X → HY → (bb)WW → bb4q

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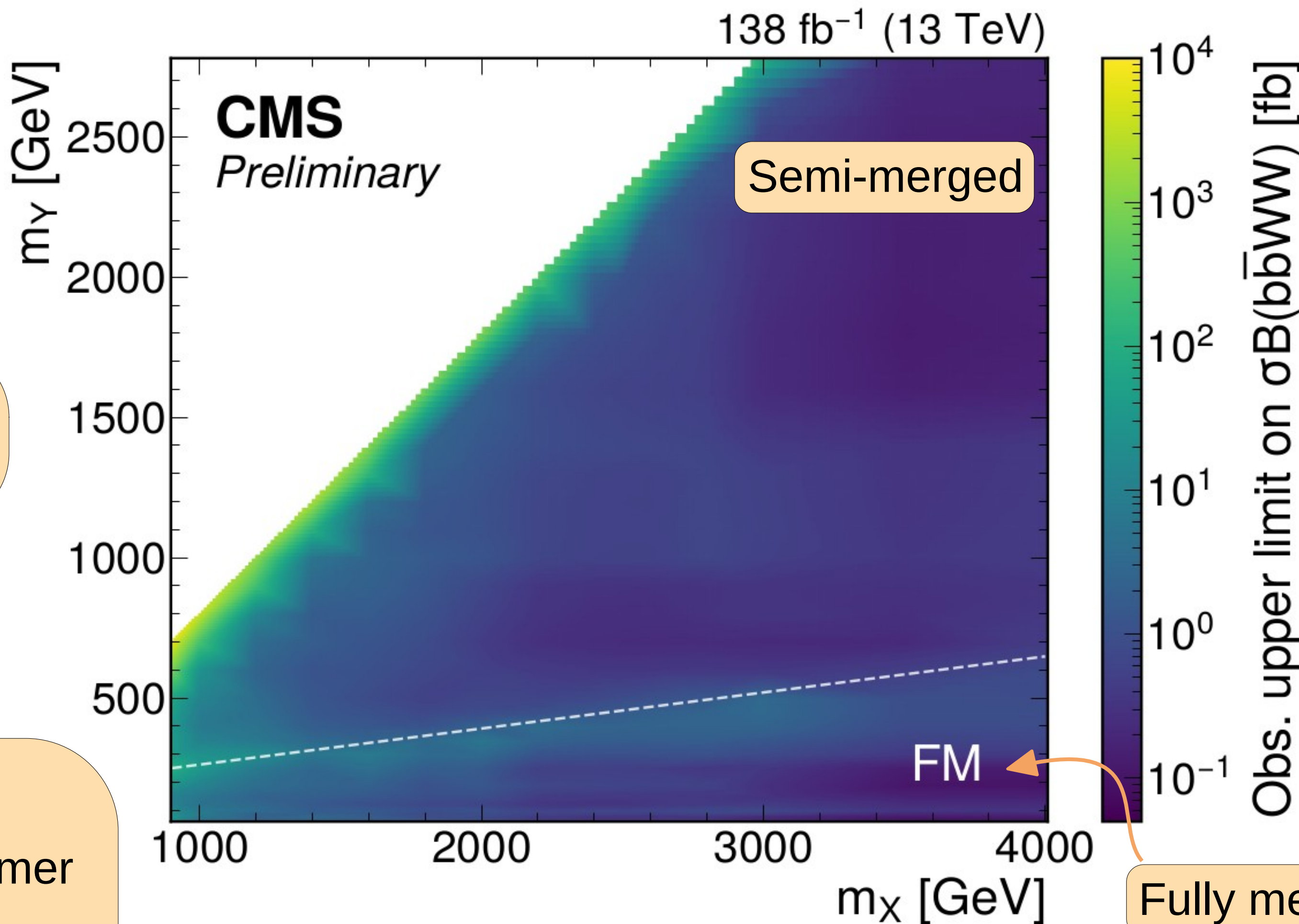
- Observed limits:



Fully merged

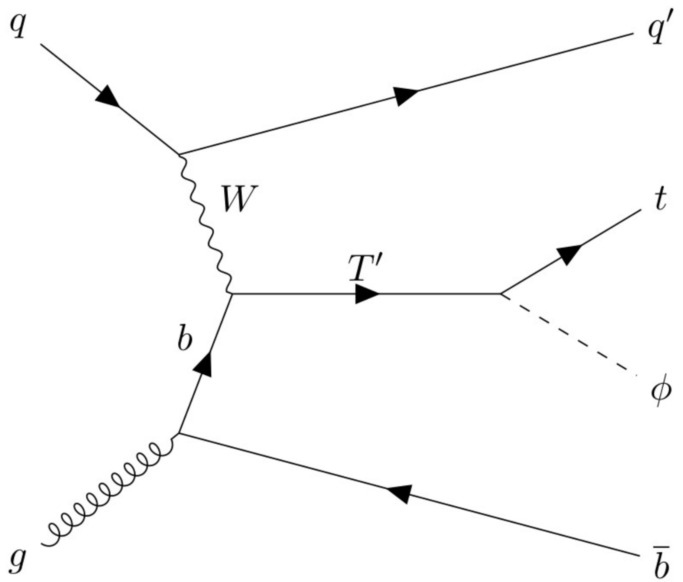
First search of its kind

First use of Particle Transformer network in resonant searches

X → top + new scalar (or H)

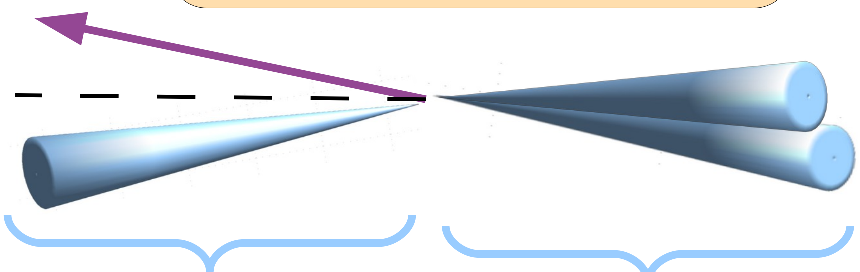
B2G-22-001

B2G-23-009



- Minimal scenario:
  $T' \to bW,\, tZ,\, tH$
- Non-minimal: add another (pseudo)scalar $\phi \to b\bar{b}$
  - If allowed, weakens limits from

Leptonic top channel



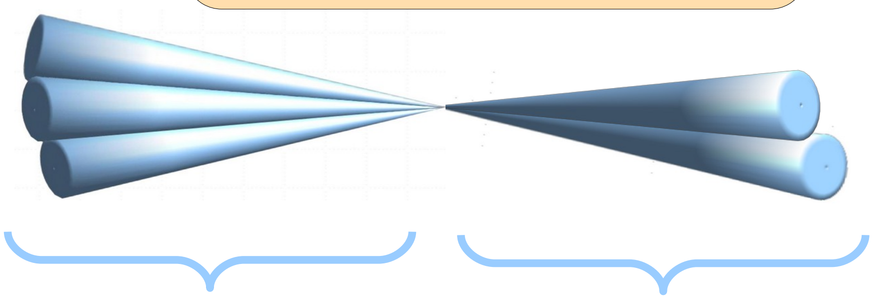
Lepton + E_T^{miss} + b jet

New, dedicated MVA

Merged $\phi \to b\bar{b}$ jet

Particle Net, mass decorr. Xbb tagger

Hadronic top channel



Top-tagged jet

Particle Net top tagger

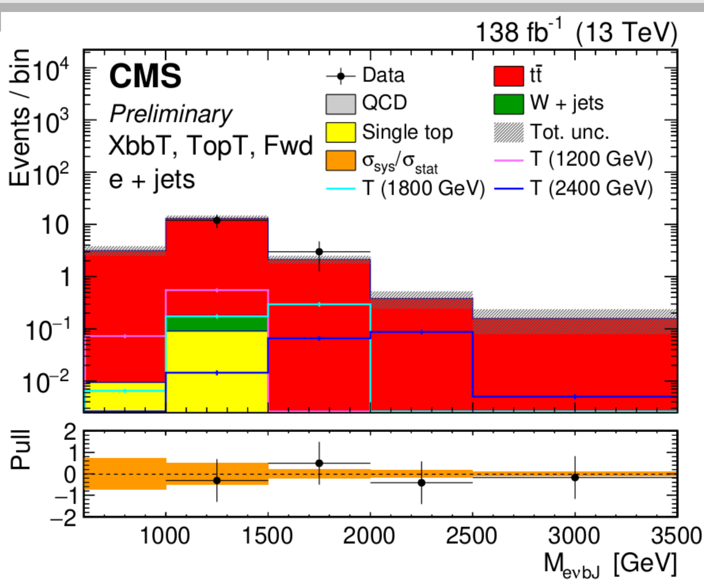
Merged $\phi \to b\bar{b}$ jet

Particle Net, mass decorr. Xbb tagger

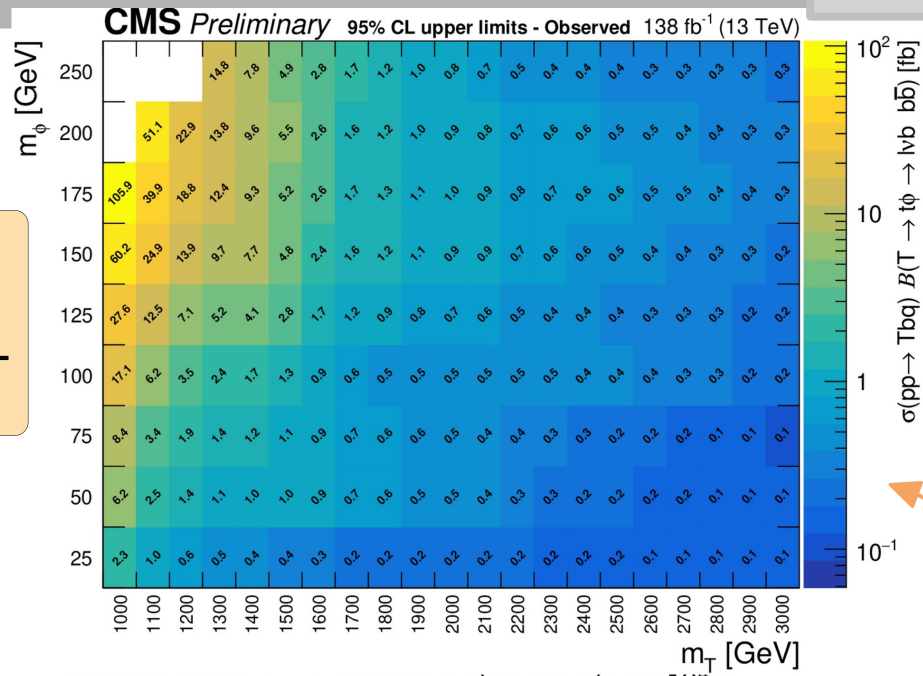
X → top + new scalar (or H)

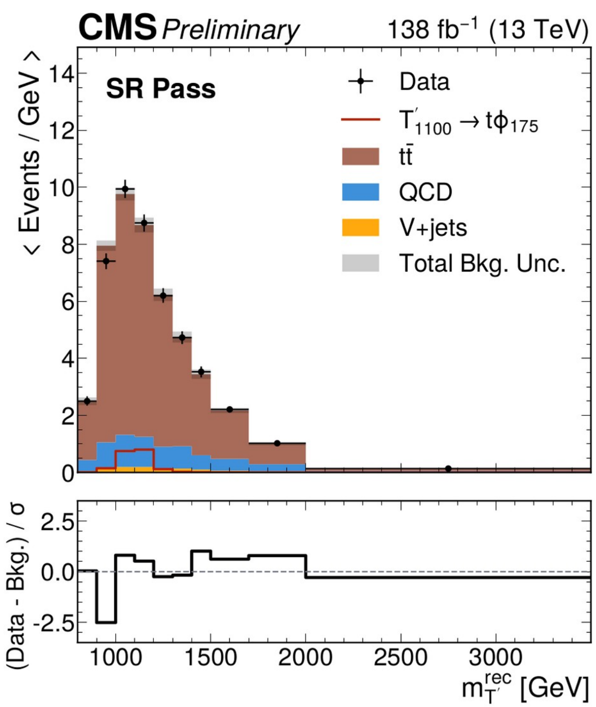
B2G-22-001

B2G-23-009

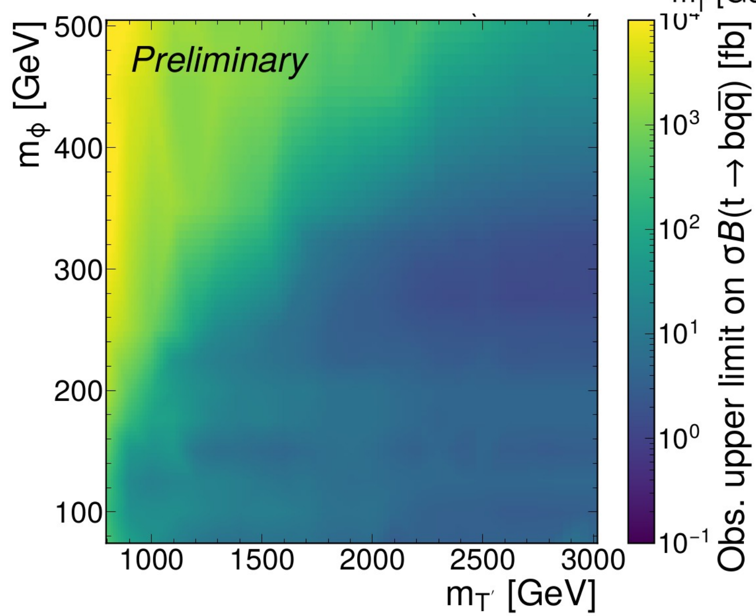


Leptonic





Hadronic



Observed limits

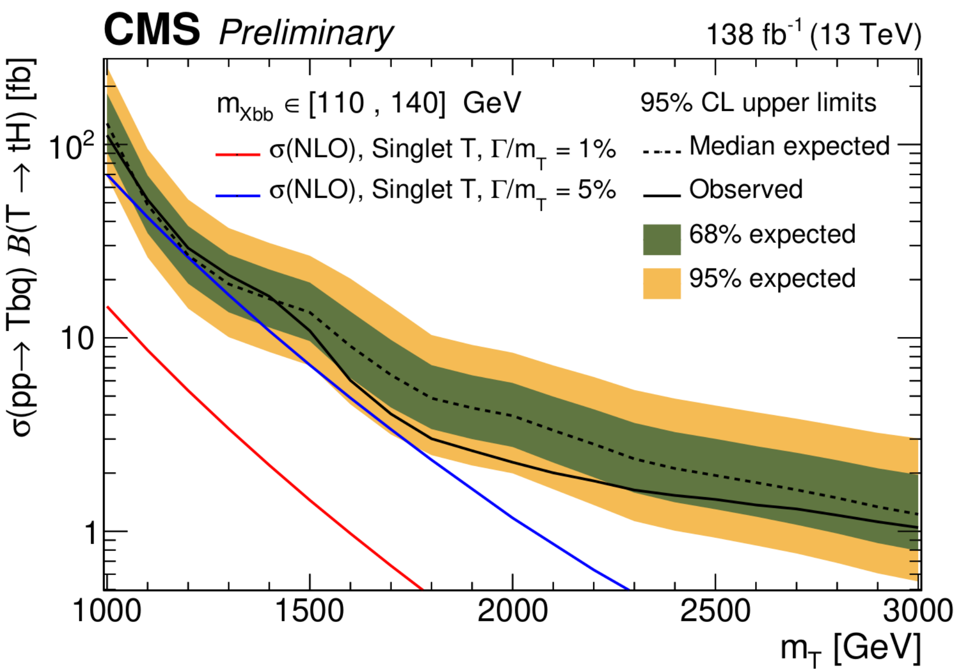
X → top + new scalar (or H)

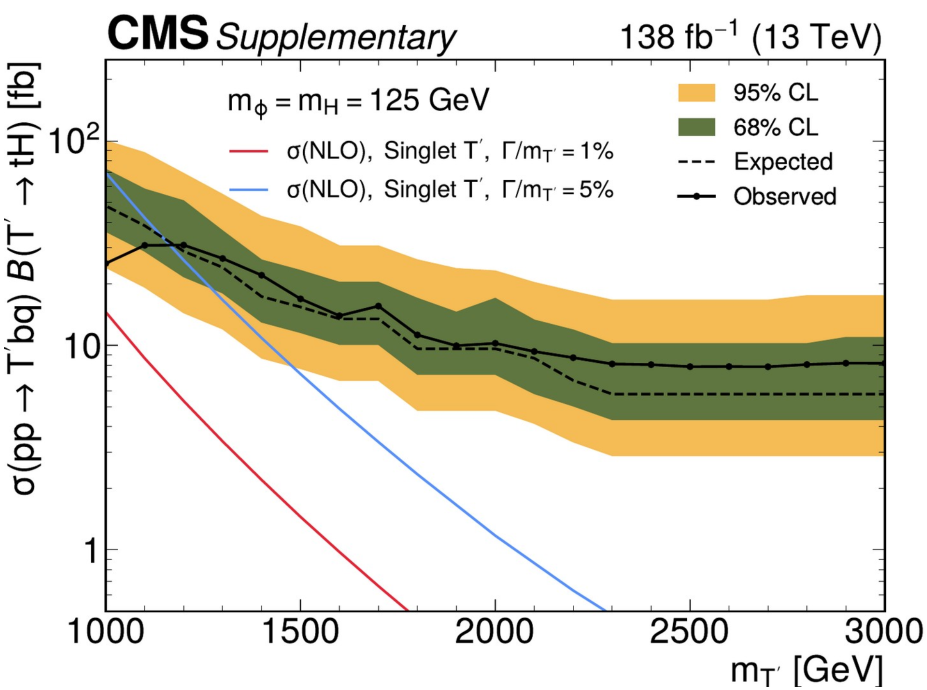
B2G-22-001

B2G-23-009

- Hadronic channel slightly better at low masses, semileptonic better at high masses
- Comparing limits for $T' \to tH$:
  - Hadronic better at low $m_{T'}$
  - Semileptonic better everywhere else

Combination in progress!



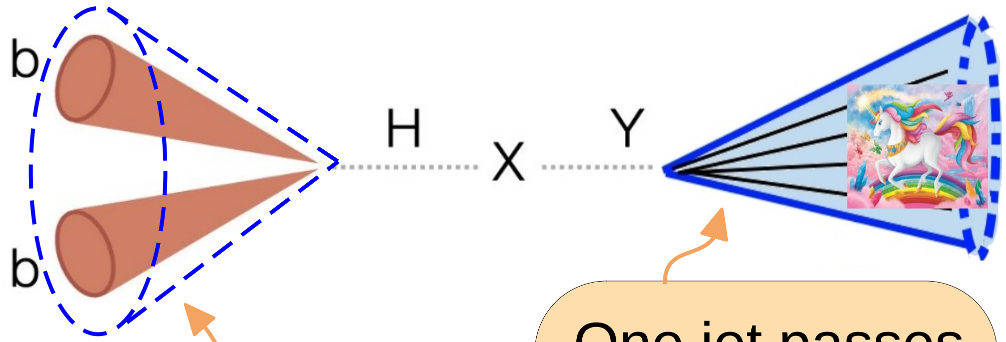


$X \to HY$, where Y is anomalous jet

- Covers many models
  - X → H(bb)Y(4q)
  - X → H(bb)Y(ud)
  - X → H(bb)Y(tt(6q))
  - T' → H(bb)t(bqq)
  - Higgs likely to be involved in many BSM scenarios

- Search for a bump in 2D (m_X, m_Y) plane

- Main backgrounds:
  - QCD – from data
  - $t\bar{t}$ – data-corrected simulation



One jet passes Variational Autoencoder

Other jet in H mass window

It also passes Particle Net Xbb tagger

Pass / Fail Ratio used in QCD bkg estimate

$X \to HY$, where Y is anomalous jet

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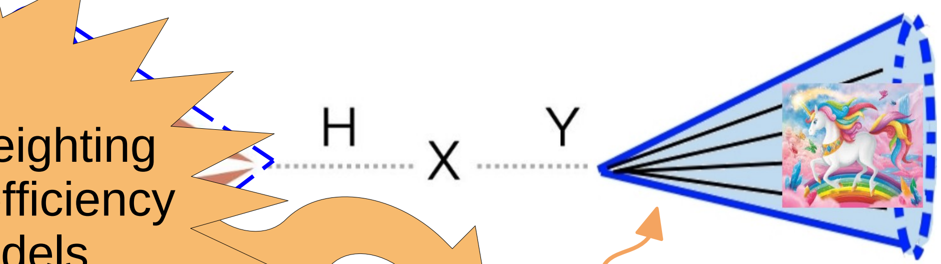
  - Higgs likely to be ... many BSM scenarios

Lund Plane Reweighting
for uncertaintyon efficiency
for specific models



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Pass / Fail Ratio used in QCD bkg estimate

- Search for a bump in 2D (m_X, m_Y) plane

- Main backgrounds:
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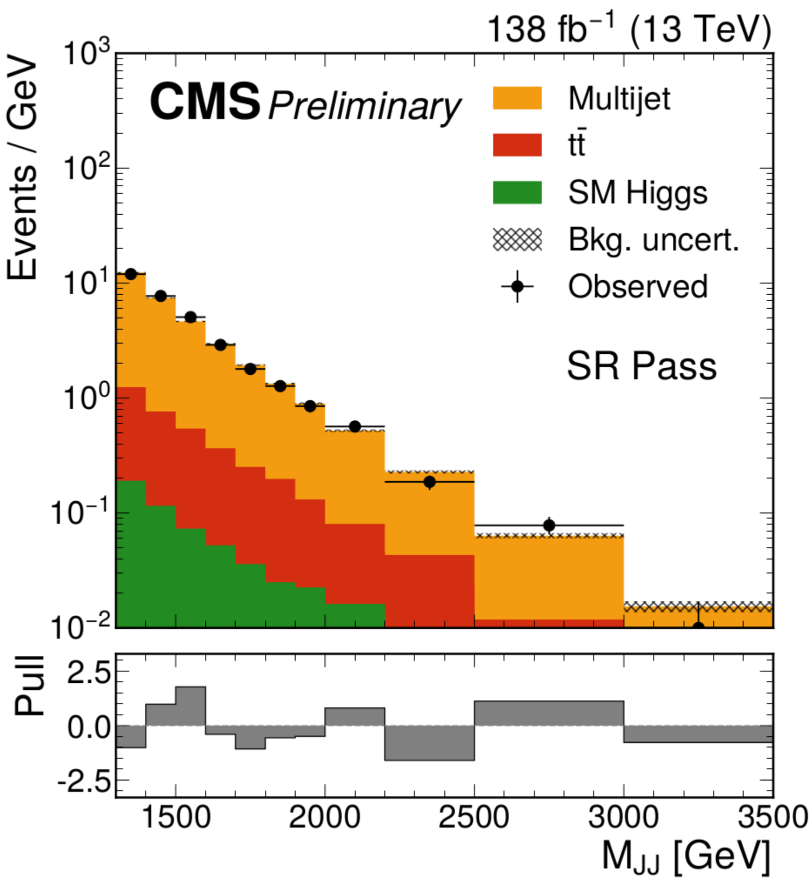
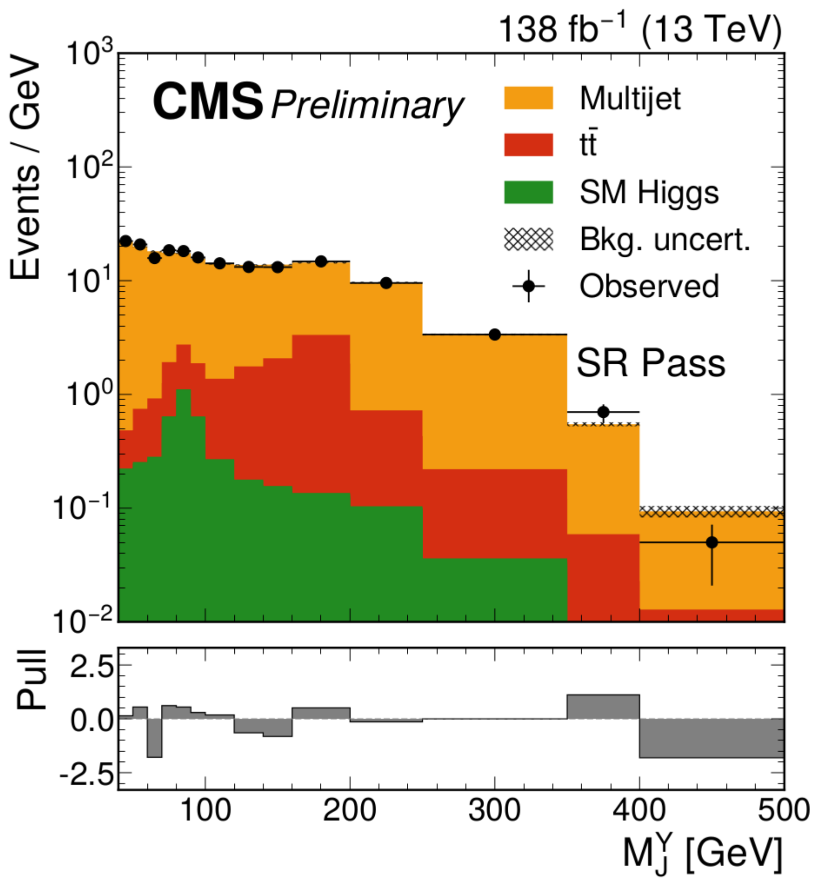
$X \rightarrow HY$, where Y is anomalous jet

- Projections of 2D "Pass" distribution onto M_X and M_Y





Multijet bkg estimated from "Fail" events:

$$n_{\text{Pass}}(i) = n_{\text{Fail}}(i) R_{\text{P/F}}(M_X, M_Y)$$

$X \to HY$, where Y is anomalous jet

- Limits set on two benchmark models

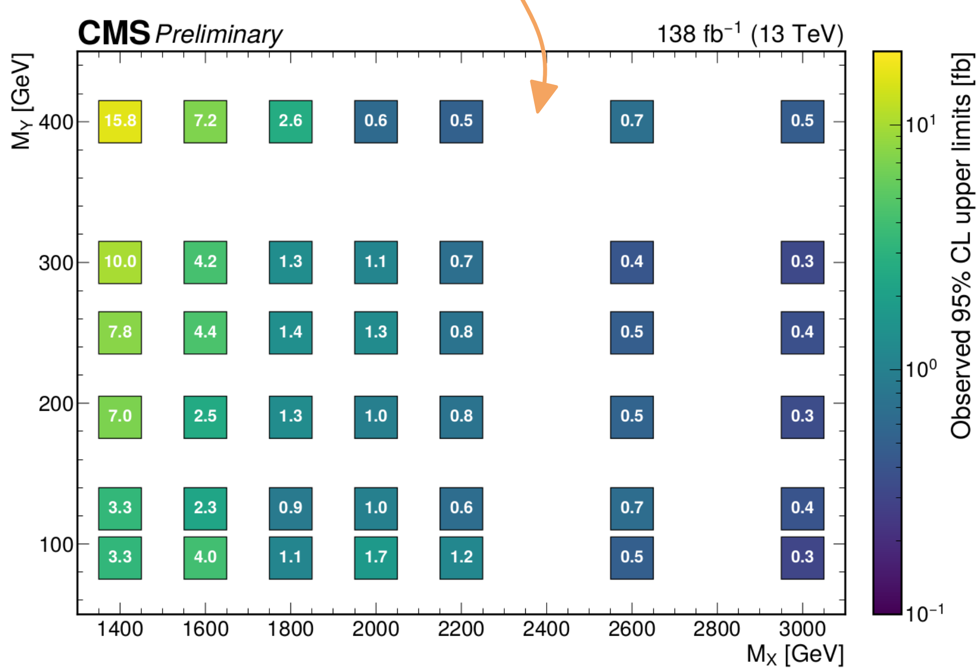
Y = WW → 4q

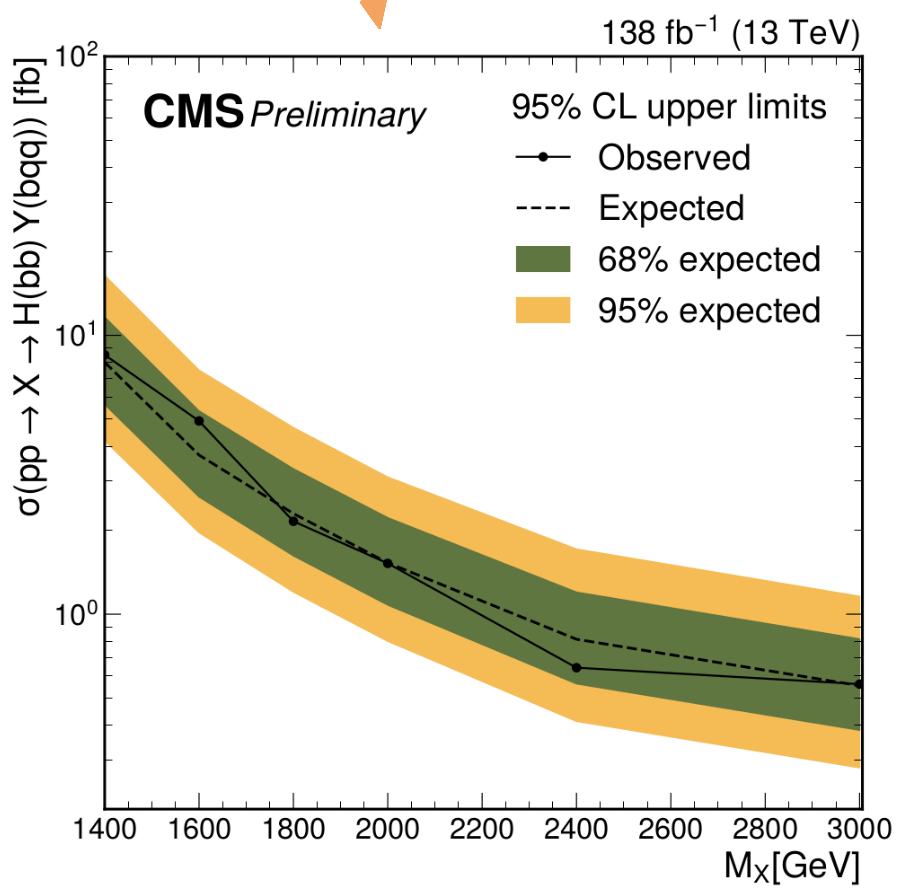
$$X \to HY \to bbWW \to bb(4q)$$

(already discussed)

VLQ: X = T', Y = top

$$T' \to Ht, t \to bqq$$





Conclusions

- A number of new interesting results in boosted channels
- New ideas, diversity of approaches:
  - New channels
  - Non-minimal models (new scalars expand BRs)
  - Continuous improvements of ML jet taggers
  - Use of anomaly detection:
    - jets with anomalous substructure used as new kind of object in `classical' searches
  - Lund Plane Reweighting opens access to new BSM signals via new `uncallibratable' jet taggers
- Run 3 data analyses in full swing

BACKUP MATERIAL

(Dijet) Resonances with anomalous jets

EXO-22-026

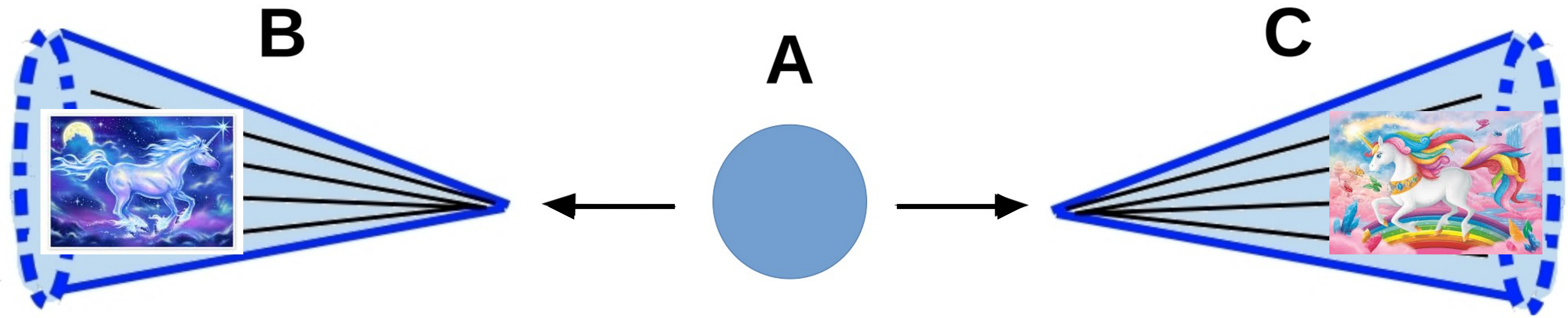
- ML-based anomaly detection techniques to tag ‘anomalous’ jets that have substructure distinct from QCD
  - Outlier detection (VAE-QR)
  - Weak supervision
    (CWoLa Hunting, TNT, CATHODE)
  - Multi-signal priors (QUAK)

- Mostly complementary
- 4 out of 5 methods entirely data driven, no use of MC
  - Anomaly detector trained directly on data!
- The first use of anomaly detection at CMS!

Resonances with anomalous jets

EXO-22-026

- Heavy particle A → B C



- What if B or C decay in unforeseen ways?

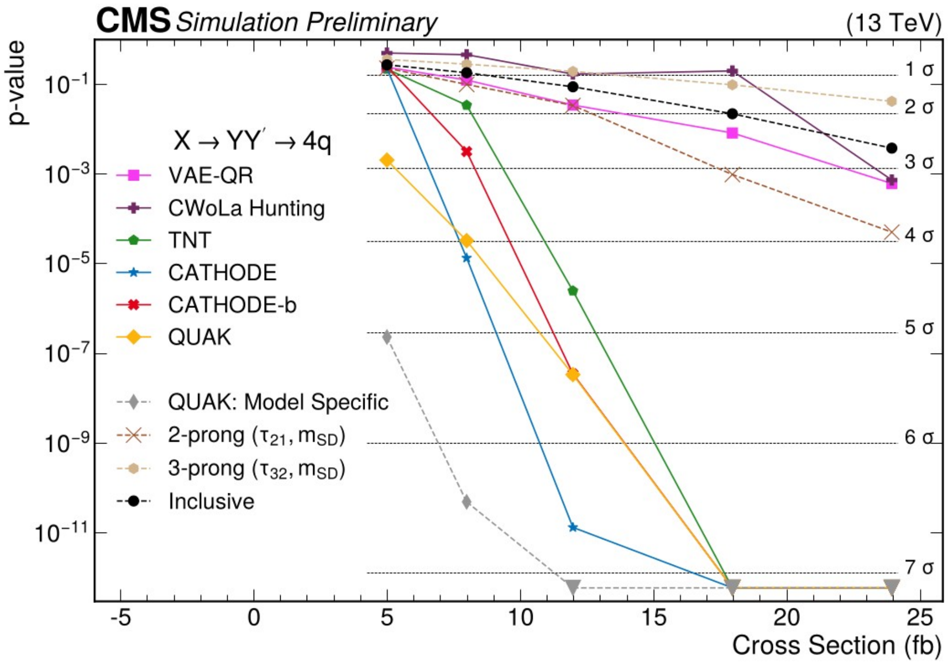
- Highly boosted → large-R jets with anomalous substructure
  - Selects events with two large-R jets
    → train anomaly detectors
    → cut on 'anomaly score'
    → bump hunt in dijet mass

Resonances with anomalous jets

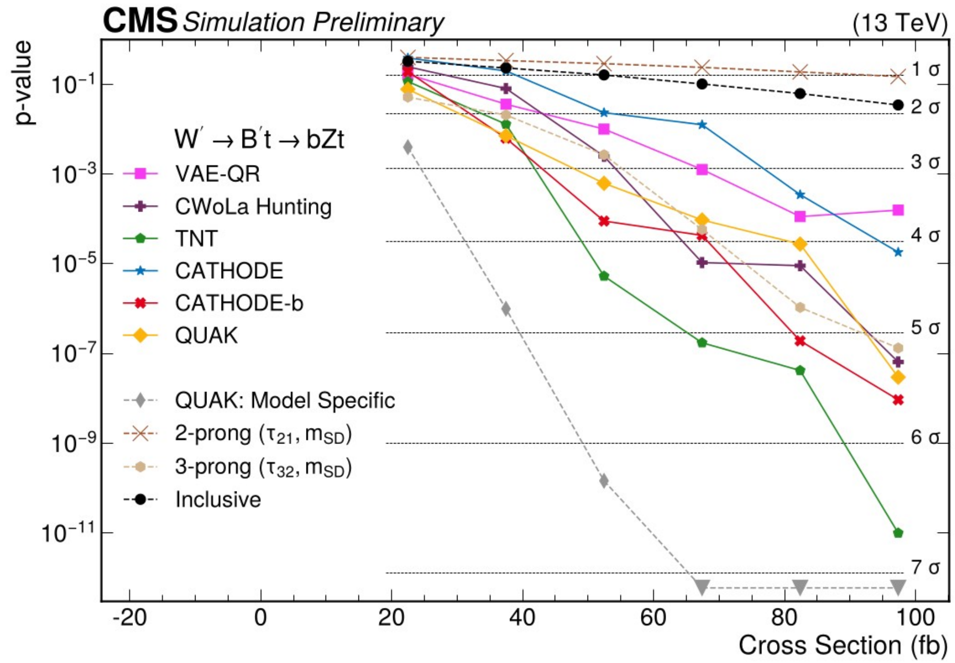
EXO-22-026

- Test methods in MC by injecting signal and running full analysis chain, then extract significance

(2+2 prong)



(3+5 prong)



- P-value vs injected cross-section

- **Anomaly methods** vs **inclusive bump hunt**, **standard cut-based approaches** and a **model-specific search**

Resonances with anomalous jets

EXO-22-026

- Bump hunt on dijet mass spectrum
- Bkg = smooth function

- 95% CL limits
- 3-7x improvement wrt incl.